Strength conditioning in older men: skeletal muscle hypertrophy and improved function

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THE REDUCED MUSCLE STRENGTH of the elderly has been attributed to aging itself and to lower physical activity that produces a decline in muscle function (15). Loss of strength may have a marked effect on the capacity of elderly men and women to lead independent lives. In the United States, surveys have shown that after the age of 74, 28% of men and 66% of women cannot lift objects weighing >4.5 kg (19). Part of the decline in strength may be due to a reduction in muscle mass (32). Resistance training in older men has been shown to produce significant gains in strength (2, 21, 27), but the evidence for the role of hypertrophy in strength gain in the elderly is not clear. The present study was designed to determine how a standard rehabilitation program for improving strength in elderly men affected the function, total mass and fiber size of the conditioned muscles, and the rate of actomyosin turnover in the whole body.

METHODS

Subjects. Twelve previously sedentary men between the ages of 60 and 72 volunteered for this study. Before being accepted a complete medical examination was carried out to exclude volunteers with conditions that could interfere with the study. The study design was explained to all subjects and an informed written consent was obtained. The experiment was approved by the Tufts University-New England Medical Center Human Investigation Review Committee. Evaluations were carried out before training and after 6 and 12 wk of training.

Training. The subjects trained each muscle group of each leg on a "thigh-knee" dynamic machine (Universal, Cedar Rapids, IA) at 80% of the one repetition maximum (1 RM) under supervision. Before training started, they had two or three practice sessions, one during the initial interview and the other(s) during the week before training. The 1 RM was measured at the end of each week on the same device used for training. The training load was readjusted for the following week to keep the training stimulus constant. The men performed three sets of eight repetitions for the extensors and flexors of each knee, at the set load, three times per week for a total of 34 training sessions (2 of the training sessions were used for testing purposes). Volunteers were instructed to perform each repetition in ~6-9 s. They were told to raise the weight with one leg in 2-3 s, pause briefly (2-3 s) after covering a range of motion of 90°, and to slowly lower the weight during the eccentric phase of the contraction (2-3 s). They were also told to pause ~10 s between repetitions and ~2 min between sets. All of the training sessions were preceded by a 10-min warm-up on a cycle ergometer at ~50% of the maximal heart rate and a 10-min stretching routine for the different muscles of the legs.

Muscle strength. In addition to weekly measurements of dynamic concentric strength (1 RM test), static and dynamic isokinetic strength of the knee extensors and flexors were measured using an isokinetic dynamometer (Cybex II) before training and after 6 and 12 wk of training. On the test day, after a period of standardized warm-up and familiarization, the subjects were encouraged to exert maximal muscular force. The machine was
calibrated every test day.

Static strength was measured at an angle of 30° of knee flexion. The fully extended knee was considered to equal a flexion of 0°. Maximal voluntary static strength was defined as the highest torque of three contractions. Dynamic isokinetic strength was measured at angular velocities of 30, 60, 120, 180, 240, and 300°/s. The subjects performed three maximal voluntary contractions at each preset velocity in random order. The highest or peak torque at each velocity was recorded. An angle-specific technique was used to describe the torque-velocity relationship (28). Peak torque measurements at 60 and 240°/s were used to represent slow- and fast-dynamic isokinetic strength, respectively.

Computerized tomography (CT scan). A CT scan of the thighs was made at each evaluation period, halfway between the pubic symphysis and the lower pole of the patella. The level of the scan coincided with the location of the muscle biopsy. The volunteers were examined in the supine position with the thighs relaxed. The position of the legs was kept constant in all three examinations. The scanner is a third-generation Siemens DR3 CT scanner (Somatom-Siemens, Erlanger, FRG) operating at 125 kV peak. Technical factors employed were slice width of 8 mm, mA·s of 520, and a scanning time of 7 s. Images were viewed at a window width of 512 Hounsfield units (H) and a level setting between 10–40 H was selected to achieve good contrast between muscle, fat, and bone.

All measurements from the CT scans were related to total thigh area, calculated from thigh circumference at the level of the biopsy. The CT images were digitized by optical density with a DeAnza Image Processing system interfaced to a Vax 11/780 computer (Digital Equipment, Concord, MA), by assigning threshold values for fat, bone, and muscle (5). This allowed the accurate measurement of total muscle area by correcting for intramuscular fat, as shown in Fig. 1. The area of the quadriceps was identified and measured by manual planimetry. Non-quadriceps area was obtained by subtracting the planimetrically measured quadriceps area from total muscle area. Values reported in the figures are for the left thigh because biopsies were obtained from the left vastus lateralis muscle.

Muscle biopsy. Muscle samples were obtained by needle biopsy from the left musculus vastus lateralis (11). One biopsy was taken at each evaluation period, and the same biopsy site was used on each occasion. The muscle specimen was placed in mounting medium (Tissue-Tek) frozen in isopentane cooled to the temperature of liquid N₂ for later sectioning and staining. Samples were sectioned by a single investigator and inspected by light microscopy to ensure that sectioning was perpendicular to the orientation of the fibers.

All biopsy samples from one individual were stained simultaneously for myofibrillar ATPase (9). The fibers were classified as type I or type II. An average of 408 fibers were counted per biopsy for determination of muscle fiber type.

Muscle fiber areas (type I and type II) were measured using manual planimetry. Muscle mean fiber area (MFA) was determined as follows: (MFA_I × %type I + MFA_II × %type II)/100, where MFA_I and MFA_II are the mean fiber area type I and type II fibers, respectively.

Urinary 3-methyl-L-histidine (3-MeH) and creatinine. The 24-h urine from the subjects was collected for 2 days during each of the evaluation periods. During each collection and the 3 previous days, the men consumed a meat-free diet but continued training. 3-MeH was measured by high-pressure liquid chromatography and used as an index of myofibrillar protein turnover (33). Creatinine was measured colorimetrically and used as an estimate of muscle mass (16).

Statistical analysis. Means ± SE were calculated. One-way analysis of variance with repeated measures and Tukey’s post hoc test were used to determine the effects of training. Pearson’s coefficient of correlation was used to express the relationship between measures of interest. Statistical significance was accepted at P < 0.05.

RESULTS

Anthropometry. There was no significant change in whole body mass or muscle mass over the training period (Table 1). By 12 wk, thigh girths at the level of midthigh, 10 cm above midthigh, and 10 cm below midthigh had all increased by an average 2.1 cm (P < 0.05), as shown in Table 1.

Muscle strength. All muscle groups showed marked improvements in dynamic strength measured with the 1 RM technique (P = 0.001), with average increments of 20 kg for extensors and 15 kg for flexors over the 12-wk period, as shown in Table 2. The percent increase was 116.7% in the right knee extensors (RE), 107.4% in the left knee extensors (LE), and 226.7% in the right and left knee flexors (RF and LF). The gain in strength per training day was 3.4% (RE), 3.2% (LE), 6.7% (RF), and 6.2% (LF). Weekly measurements of 1 RM of the LE and LF are shown in Fig. 2.

Dynamic strength measured isokinetically at 60°/s showed an 8.5% improvement for RE, a 10.0% increase for LE, 14.6% for RF, and 18.5% for LF. At 240°/s all muscle groups also showed significant improvements. The RE increased 16.0%, LE increased 16.5%, and the RF and LF showed an 18.2 and 14.7% improvement, respectively.

Torque-velocity curve. Training resulted in an upward displacement of the torque-velocity curve with its greatest influence on the slow-velocity high-torque region of the curve (0–60°/s), as shown in Fig. 3 for the LE.

Muscle size. The increase in thigh muscle cross-sectional area over the 12-wk period, measured by image analysis of the CT scan, is shown in Fig. 4. The increase in the cross-sectional area of the quadriceps, measured by planimetry, is shown in Fig. 5. Significant increases were found after 6 wk of training. After 12 wk, the increases were 9.8% for right muscle area, 11.4% for left muscle area, 11.9% for right quadriceps area, and 9.3% for left quadriceps area.

The analysis of the muscle biopsies showed a progressive increase in fiber area with training (Fig. 6). By week 12, the area of type I fibers had increased by 33.5% and the area of type II fibers by 27.6%. The ratio of type II
FIG. 1. Sample pictures of computerized tomographic scan at midthigh (A) and digitized image showing muscle, fat, and bone (B).

TABLE 1. Anthropometric changes in elderly men with strength training

<table>
<thead>
<tr>
<th></th>
<th>Pre week 0</th>
<th>Mid week 6</th>
<th>Post week 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body wt, kg</td>
<td>78.0±2.1</td>
<td>78.1±1.9</td>
<td>78.5±1.9</td>
</tr>
<tr>
<td>Muscle mass, kg†</td>
<td>27.8±1.3</td>
<td>27.9±1.5</td>
<td>28.7±1.3</td>
</tr>
<tr>
<td>Left thigh girth, cm</td>
<td>56.5±0.8</td>
<td>57.8±0.9</td>
<td>58.6±0.9†</td>
</tr>
<tr>
<td>Upper thigh</td>
<td>49.3±0.2</td>
<td>50.9±0.7</td>
<td>51.6±0.7†</td>
</tr>
<tr>
<td>Midthigh</td>
<td>40.9±0.6</td>
<td>42.0±0.7</td>
<td>42.5±0.8†</td>
</tr>
<tr>
<td>Lower thigh</td>
<td>40.9±0.6</td>
<td>42.0±0.7</td>
<td>42.5±0.8†</td>
</tr>
</tbody>
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Values are means ± SE. Midthigh measurement was taken at site of computerized tomography scan and biopsy, and upper and lower thigh measurements were taken 10 cm above and below, respectively. * Different from Pre (P < 0.05); † from urinary creatinine (21).

Strength gains in the elderly. One of the major findings of this study was the large and progressive increase in 1 area to type I area remained unchanged. The initial proportion of type II fibers was 45.9% and did not change with training.

Urinary 3-MeH. The excretion of 3-MeH increased 39% from 2.73 ± 0.19 to 3.55 ± 0.37 μmol·kg⁻¹·day⁻¹ with training (P < 0.05). Actomyosin protein turnover per unit muscle mass (i.e., per gram of urinary creatinine) increased 38% from 141 ± 9 to 182 ± 20 μmol 3-MeH/g creatinine (P < 0.05). Urinary creatinine did not change with training; values were 1.50 ± 0.07 g/day initially and 1.55 ± 0.07 g/day after 12 wk of training.

DISCUSSION

Strength gains in the elderly. One of the major findings of this study was the large and progressive increase in 1
TABLE 2. Changes in muscle strength with training

<table>
<thead>
<tr>
<th>Muscle Group</th>
<th>Pre</th>
<th>Mid</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right extensors</td>
<td>20±2</td>
<td>31±2†</td>
<td>40±2†</td>
</tr>
<tr>
<td>Right flexors</td>
<td>8±1</td>
<td>18±1*</td>
<td>23±2†</td>
</tr>
<tr>
<td>Left extensors</td>
<td>26±1</td>
<td>32±2*</td>
<td>40±2†</td>
</tr>
<tr>
<td>Left flexors</td>
<td>8±1</td>
<td>18±1*</td>
<td>23±2†</td>
</tr>
</tbody>
</table>

Values are means ± SE. Dynamic strength was measured with 1-repetition maximum technique; static and isokinetic strength were measured with a Cybex dynamometer. For each muscle group and testing modality: * different from Pre (P < 0.05); † different from Mid (P < 0.05).

RM, amounting to an average 5% improvement per training day. The rate of dynamic strength gain per training session in these elderly men was similar to the 4.4–5.6% increase in dynamic strength per session observed in young men (average age 28 yr) after a similar training protocol (30) and comparable to gains reported for young men in other studies (8, 27, 31). Various strength-training studies in older subjects, using different training and testing methods, have shown strength gains per training day that ranged from 0.9 to 4.2% (20, 27). The relative gain in strength could in part have been determined by low initial values. The results suggest that marked and rapid functional improvement can be obtained in the elderly with a standard strength rehabilitation protocol.

The gain in strength measured by 1 RM was ~10 times greater than the strength gains measured with the isokinetic testing modes, and the gains did not correlate with each other. Since the 1 RM method used the same device and motor patterns that were being employed during training sessions, it is likely that the lack of relationship between improvements in 1 RM and other strength measurements was because of neural adaptations specific to the type of training. The torque-velocity relationship provides further evidence to support the notions of specificity of training and neural adaptation. Training had its greatest influence on the slow-velocity high-force region of the curve. This was similar to the range used during training; although speed of movement during the training sessions was not measured, it can be estimated from the duration of each repetition (6–9 s) and the range of motion (90°).

Specificity of training has been described by various authors (6, 8). Dons et al. (8) found no change in static strength after 7 wk of dynamic strength training in young healthy men, although there was a 42% increase in the 1 RM, which is a test similar to the type of exercise used during training. Coyle et al. (6) found no change in static strength in two groups of young men who trained for 6 wk with slow- or fast-isokinetic contractions, despite a significant increase in isokinetic strength. The group that trained at slow speeds (60°/s) did not show improvements during fast contractions (300°/s), and the group that trained at fast speeds did not show improvements during slow contractions. The torque-velocity curve obtained in the present study agrees with the findings of Caiozzo et al. (5), who found that training at slow speeds resulted in greater adaptations in the slow-speed range of the curve. These studies show that tests that mimic the speed and characteristics of the movements used during training demonstrate the greatest enhancement of force generation. Specificity in strength gain has been shown for type of contraction (10) and velocity of movement (6). In addition, there is a dissociation between gains in maximal voluntary force and electrically evoked tetanic tension (7). The evidence suggests that neurological factors contribute significantly to the increase in strength. Neural adaptation is further demonstrated by studies that show no changes in muscle morphology despite gains in strength (6, 31). In older men, strength gains have been attributed entirely to neural factors (27), but the exclusive role of neural factors is not supported by the findings of the present study.

Changes in skeletal muscle. An increase in muscle size with strength training was demonstrated at the macroscopic and microscopic level. The CT results before training for total thigh area, total muscle area, and
Effects of strength training on torque-velocity curve of left knee extensors. Results are means ± SE for pre- (-•-), mid- (-□-), and posttraining (-○-). * Posttraining values different from mid- and pretraining (P < 0.05); † posttraining values different from pretraining (P < 0.05).

Changes in thigh muscle cross-sectional area of right and left leg from image analysis of computerized tomography scans. Results are means ± SE. * Different from pretraining measurements (P < 0.05).

Changes in quadriceps muscle cross-sectional area of right and left leg from planimetric analysis of computerized tomography scans. Results are means ± SE. * Different from pretraining measurements (P < 0.05).

The increase in strength and in muscle area found in the present study is greater than has previously been described for elderly men (27). The discrepancies can be explained by differences in training intensity and duration and in techniques used to measure muscle size. The study of Moritani and deVries (27) involved 24 training sessions with 20 repetitions/session at 66% of 1 RM, whereas the present study involved 34 sessions with 24 repetitions/session at 80% of 1 RM. Their technique for calculating muscle size was based on skinfolds and girths and not on direct visualization of muscle.

At a microscopic level, the present study showed significant hypertrophy of both type I and type II fibers (Fig. 6). Previous strength-training studies have reported inconsistent effects on fiber area. In young men, some studies have shown greater hypertrophy of type II fibers (31), but MacDougall et al. (26) showed similar hypertrophy of both type I and type II fibers. Aniansson and Gustafsson (2) reported no change in type IIa and type IIb fiber area, mean fiber area and fiber area ratio, and a decrease in total type I fiber area in 12 69- to 74-yr-old men, who trained the lower extremities three times per week for 12 wk. However, the training program was of low intensity, and the strength component only included dynamic exercises using body weight and no special equipment as resistance. Strength gain of the quadriceps was 9–22%, and the increase in total type II area was a result of increased percentage of type II fibers. Another
error in measuring fiber area may also explain the dis-crepancy between CT values and fiber size. The coeffi-
cient of variability for serial biopsies is lo-20% (3, 14).
crepancy between fiber type distribution and strength in the elderly shows contradic-
tory results in the literature. Grimby et al. (13) reported a significant relationship between the percentage of type II fibers and strength in a population of elderly men. However, in the present study no relationship was found between the proportion of type II fibers at the onset of training and initial strength or rate of strength gain, in agreement with findings of Aniansson et al. (1) and Larsson et al. (22).

In the present study, the increases in both type I and type II area averaged 28.2%, whereas the increase in muscle area shown by CT scan averaged 10.6%. There was no significant correlation between the macroscopic changes in total muscle and the increase in fiber area. The fact that changes in muscle size did not correspond to changes in muscle fiber area is supported by studies of muscle hypertrophy in animals. In rats, the weight of the exercised muscles is not necessarily greater than the control muscles even though the fibers are considerably larger, suggesting that the fibers develop at the expense of the extracellular compartment (12). Methodological error in measuring fiber area may also explain the discrepancy between CT values and fiber size. The coefficient of variability for serial biopsies is 10–20% (3, 14).

In addition, changes in the biopsy sample taken from the vastus lateralis muscle may not reflect the average hypertrophy of other fibers or the entire quadriceps.

**Actomyosin protein turnover.** In experimental animals, strength training of a single limb has shown that muscle hypertrophy occurs by a rapid and marked increase in protein synthesis together with a slight increase in protein breakdown (23). In humans, the turnover of muscle proteins has been estimated from the excretion of 3-MeH, a modified amino acid that is found in actin and myosin (33). Because 3-MeH excretion reflects the breakdown rate of all contractile proteins, it cannot be considered an exact measurement of skeletal muscle breakdown only (29). However, the results of the present study suggest that changes in urinary 3-MeH were due to an increase in skeletal muscle mass and/or to increased turnover of actomyosin, most likely in the muscles that showed evidence of hypertrophy. The lack of change in urinary creatinine suggests that local changes in muscle mass were not sufficient to cause a detectable increase in whole body muscle mass (Table 1). However, the increase in 3-MeH excretion was significant. Daily 3-MeH excretion for the 12 elderly men before training was 212 ± 16 μmol/day, similar to the 224 ± 11 μmol/day reported for 17 young sedentary men (24). Expressed per unit of muscle mass, the final value of 182 ± 20 μmol 3-MeH/g creatinine was greater than the 132 ± 3 μmol 3-MeH/g creatinine reported for young weight-trained men (24) and similar to the value of 187 ± 13 μmol 3-MeH/g creatinine reported for young weight-trained men (17).

Although this could be due to acute effects of an exercise session during or immediately before urine collection, a single weight-training bout has not been found to alter 3-MeH excretion (18). The progressive increase in 3-MeH excretion in the elderly men suggests that muscle hypertrophy was accompanied by an increase in actomyosin turnover.

**Conclusion.** A vigorous strength training program, similar in nature to standard rehabilitation techniques, caused a marked gain in strength in older men. Strength training led to muscle hypertrophy, due to an increase in the size of type I and type II fibers. Muscle hypertrophy was accompanied by an increase in the rate of actomyosin protein turnover. These results show that the capacity for increasing muscle mass is retained in old age and that the improvement in strength is partly due to muscle hypertrophy.

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